neutron-absorbing fission products. Such a near-breeder reactor would not need any fuel after the initial fuel charge (less than 400 tons of natural uranium oxide).

An advantage of this reactor would be that its technology is essentially known (although the use of enriched fuel and thorium would require some modification of the present Candu), and therefore its cost would also be predictable. A more advanced reactor using uranium-233 and thorium is the molten salt reactor [24] developed at Oak Ridge. This reactor, using technology which has only been demonstrated on a laboratory scale, reprocesses the molten fuel continually, and thereby achieves a (small) breeding gain.

The other solution of the uranium supply problem is, of course, the fast breeder, using a mixture of plutonium and uranium. As is well known, this is still under development. But, in contrast to controlled fusion, we *know* that it works: many experimental breeder reactors in many countries have worked very satisfactorily, notably the Experimental Breeder Reactor II in Idaho which has operated continuously since 1963. In the next stage of development, the French demonstration reactor Phenix has worked extremely smoothly for over two years.

Some technical problems remain to be solved, such as trouble-free and efficient heat transfer from the sodium coolant to water in the steam generator. The economics must be improved, compared with the Clinch River Demonstration Reactor which is to be built soon. While some of the projections on economics may be too optimistic, I believe that the price is likely to be less than $1\frac{1}{2}$ times that of a light water reactor. At this level, it will be economical once we have to use uranium from low-grade ores, such as Chattanooga shale which may cost as much as $150 a pound.

The great advantage of the breeder is its very low consumption of uranium (or thorium). Not only does a given amount of uranium give about 60 times as much energy as it would in a light water reactor, but it becomes justifiable, both economically and environmentally, to use very low-grade ores such as granite. Including just the best grade, Conway granite, the United States would have enough uranium for 40,000 years. The breeder thus provides an essentially inexhaustible energy source.

For this reason, I consider the fast breeder the best solution of the uranium supply problem. But I want to repeat, it is not the only one.

I want to conclude with a statement by Governor Brown of California [25], "The role of the leader is to help shape the discussion of national issues and not help foster unreal thinking." Too often unreal thinking on energy has dominated discussion by political leaders as well as the press.

Notes

1. U.S. Geological Survey, Publication 725.

2. The contrary view was expressed by Barry Commoner in *The Poverty of Power: Energy and the Crisis* (New York: Knopf, 1976). He gives the U.S. oil resources as 325 billion barrels. Commoner's view seems to be based on a dispute, several years ago, within the U.S. Geological Survey, between M. King Hubbert and A. D. Zapp. Hubbert has circulated privately his comments on the Commoner article. He says, "A more erroneous and misleading interpretation of the account of the petroleum estimates by Hubbert and Zapp would be difficult to devise." In any case, this dispute is a thing of the past. In the last two years, the entire U.S. Geological Survey, as well as independent groups, have come down to about the same figures as Hubbert predicted years ago, and which are listed above.

3. M. King Hubbert, U.S. Senate Committee on Interior and Insular Affairs, Serial 93-40, U.S. Government Printing Office, 1974. M. King Hubbert, "Degree of Advancement of Petroleum Exploration in United States," *American Association of Petroleum Geologists Bulletin*, 51:11 (1967), 2207-2227.

4. One quad is short for one quadrillion (10^{15}) British thermal units (Btu). One quad of oil, at present prices, costs about $2 billion. One million barrels of oil per day corresponds to about two quads per year.

5. Our undiscovered resources of gas are believed to be larger than of oil, enough for about 40 years at present consumption (U.S. Geological Survey, report no. 725, 1976). But at present our scarcity is more acute.

6. *A Time to Choose: America's Energy Future. Final Report by the Energy Policy Project of the Ford Foundation* (Cambridge, Mass.: Ballinger Publishing Co., 1974).

7. ERDA, *A National Plan for Energy Research, Development and Demonstration: Creating Energy Choices for the Future*, report 76-1, 1976.

8. Chauncey Starr, "The Year 2000: Energy Enough!," *Environmental Protection Research Institute Journal*, June 1976.

9. Federal Energy Administration, *National Energy Outlook*, 1976.

10. Atomic Energy Commission, *Nuclear Power Growth, 1974-2000*, WASH-1139, 1974.

11. Detailed statistical research by J. D. Balcomb of Los Alamos Scientific Laboratory has shown that it is the mountain states, from New Mexico to Montana, where solar heating could make the greatest contribution, not the southern states.

12. H. A. Bethe, "The Necessity of Fission Power," *Scientific American*, 234 (Jan. 1976), 21.

13. Alan D. Poole and R. Williams, "Flower Power: Prospects for Photosynthetic Energy," *Bulletin of Atomic Scientists*, May 1976.

14. M. J. Antal, Jr., "Tower Power: Producing Fuels from Solar Energy," *Bulletin of Atomic Scientists*, May 1976.

15. Information from G. E. Brandvold of Sandia Laboratory.

16. W. G. Pollard, "Long-Range Prospects for Solar Energy," *American Scientist*, 64 (1976), 424.

17. See, for example, R. A. Schmidt and G. R. Hill, "Coal: Energy Keystone," *Annual Review of Energy*, 1 (1976), 37.

18. C. L. Comar and L. A. Sagan, "Health Effects of Energy Production and Conversion," *Annual Review of Energy*, 1 (1976), 581.

19. This would permit reprocessing plants shared between several nations of a region (such as South America), as proposed by the former Secretary of State Henry Kissinger.

20. Atomic Energy Commission, *Reactor Safety Study*, WASH-1400 (Washington, D.C.: Nuclear Regulatory Commission, November 1975).

21. Atomic Energy Commission, Nuclear Plant Cost, WASH-1345, 1974.

22. M. B. Spangler, Chief, Cost-Benefit Anaylsis Branch, U.S. Nuclear Regulatory Commission, March 1976.

23. ERDA report 76-1, p. 47.

24. A. M. Perry and A. M. Weinberg, "Thermal Breeder Reactors," *Annual Review of Nuclear Science*, 22 (1972), 317.

25. The New Yorker, Sept. 13, 1976, p. 117.

Nuclear energy and our future

Robert F. Bacher

The energy crisis of 1973 brought home to everyone the degree to which we have become dependent on mideastern oil. In the past three years that dependence has increased markedly and the immediate prospect is for a further increase. That this is a serious situation is emphasized by a statement of Jimmy Carter in the presidential campaign that he would urge that a new oil embargo by the OPEC nations be countered by a complete embargo by the United States.

This points up the crisis nature of our oil shortage at home. But the problem for oil, gas, coal, uranium, solar heating, geothermal and all other short- and long-term sources of energy is not only an immediate problem but a problem that will plague us for the almost indefinite future. Technical people have pointed out these problems for many years, but with oil at $2 a barrel and all demands being met, it took the oil embargo to make people realize the precarious future. We have lived in an age in which gas and oil replaced coal, and we lived as if there would be no end to it.

So far our government has failed to adopt any long-range energy plan, and there does not seem to be much chance of such a plan in the near future.

Now we have the multiple problems of dealing with a fivefold increase in the cost of oil, a three- or fourfold increase in coal costs, a forthcoming large increase in gas costs, increased costs of construction and costly environmental protection for both coal and nuclear fission power. Within the United States our production of oil and gas is now decreasing and there is very little prospect that this trend will not continue, although perhaps at a slower rate.

This situation clearly calls for a strategy which recognizes the seriousness and complexity of our energy problems. Principal dependence on no single source of energy will give us an adequate solution either now or for the long-term future. If we concentrate entirely on our present problems without looking ahead 50 years, we will neglect again, as we have in the past, to do the fundamental work that must be done to determine whether some of the sources such as fusion and solar-electric energy can be made both technically and economically feasible.

For the immediate future, conservation is more important than any other program. We have used and wasted energy because of its very low cost compared to other products. Numerous industries report that they have already lowered their energy use by 15 percent or more. While every source of conservation helps, we must realize that roughly 40 percent of our energy is used in industry and 25 percent in transportation. No conservation program can be very successful without major savings in these two areas.

There are real possibilities of longer range savings in greater gasoline mileage for automobiles and for wholly new large-scale plants for basic industries such as steel which might save 30 or 40 percent for a given output. Our agricultural production depends in major part on mechanization, fertilizer, irrigation and greater energy use. There seems to me to be no prospect that we will move to a zero energy growth economy. The 4 percent annual growth in total energy use of the 1960s is out of the question for the future. The roughly $3^1/_4$ percent long-term growth rate is also too high. Hopefully, we in the United States can get down to a growth rate of 2.5 percent or somewhat less for total energy.

If we look at where this takes us in the next 30 years, it becomes very clear that we are going to need greatly increased use both of coal and nuclear fission energy, even if we make major efforts to increase our own oil and gas production. Both coal and nuclear energy are most suitable for major station use such as electrical energy production. Both have problems associated with their use. Power plants whether coal or nuclear require very large capital investments for the plants themselves and for the fuel handling and environmental protection equipment now required. Time schedules are longer for nuclear plants.

I have studied several summaries of costs for coal and nuclear plants and the latter seem to require a somewhat larger capital investment, but the current difference seems to be between 10 and 20 percent for comparable installations. There is more than this amount of variation among nuclear plants or coal plants themselves. Considering fuel costs, at present rates and future contracts, light water reactors give somewhat lower power costs in toto.

A very important question is whether nuclear power has properties and consequences which should preclude or greatly postpone its use. At present, roughly 2 percent of our total energy or 8 percent of our electric energy comes from light water nuclear reactors (LWR). It is now, I believe, generally recognized that nuclear reactors under normal operating conditions do not constitute a radiation contamination hazard either to workers or to those who live nearby.

A second and more serious problem which has been raised is that nuclear reactors may get out of control and explode. Present-day reactors with low enriched uranium-235 will not give a nuclear explosion. Various accidents are possible and those have been examined in great detail in the preliminary Rasmussen report. The American Physical Society's Study Group on Light Water Reactor Safety examined the preliminary Rasmussen report, and made some valid comments which were later incorporated in the final report. The probabilities of accident are very, very small and I believe that these probabilities can be further reduced, and particularly that the magnitude and the consequences of accident can be further diminished. I believe that we should go ahead with light water reactors now, paying attention to site location and particularly continuing work to increase safety still further. It is good that ERDA has budgeted a larger increase in the funds devoted to this work than to any other for nuclear work.

A third difficulty with reactors is

that the nuclear wastes contain radioactive materials which retain their activity, although greatly diminished, for a very long time. For the most part at present, spent nuclear fuel elements are being stored and not reprocessed. This fact, and the fact that no finally approved method of reprocessing and final storage has been announced, has prompted widespread critical statements that this is a crisis.

Storage for several years, probably five or more, will probably be a part of any reprocessing of fuel elements to allow the radioactivity to decay to a very small fraction of what it was initially. There have been difficulties with reprocessing plants but such difficulties have been solved in the past, and these can also be solved. The incorporation of the residues in boro-silicate glass, sealing these in stainless steel and deposition under inspection in a salt cavern in New Mexico is, I believe, a satisfactory solution, and there are probably others.

Finally, there is the problem that a large nuclear industry may increase the probability of nuclear weapons proliferation or of terrorist seizure of weapons or weapons material. I believe this to be the most serious difficulty for the mid-term future. As to seizure, the United States has greatly increased its security and safety measures under which bombs are transported, and the same methods can be used for fissionable material. Highly radioactive material is not an attractive object to seize.

Proliferation is a real problem, but not one which will be determined by U.S. action alone. I believe that every effort should be used by our country to centralize locations where separated fissionable material suitable for weapons production is handled and prepared. This is a serious international problem and the widespread construction of facilities around the world which will reprocess fuel elements and separate plutonium should be vigorously discouraged. Our unilateral action will not solve this problem. Other nations are now deeply committed to nuclear reactors and to reprocessing. We can probably have greater impact if we are a part of this group rather than outside it, but I do not favor plutonium recycle for light water reactors.

It has been argued that there isn't enough uranium to support a nuclear power industry. Others have argued that there is so much uranium (at a price) that it will not be necessary to go ahead with the breeder reactor program which expands the uranium base by about a factor of 60. Statements about raw materials availability are notoriously hazardous. If a light water nuclear reactor program is aimed at 500 or 600 reactors by the year 2000, which is within the range set by ERDA in its revised plans, then it looks doubtful to me that we can count on adequate uranium for the next 25 to 35 years.

Accordingly, I believe that we should go ahead with development work and prototype construction of the breeder, including plutonium recycling but without committing ourselves now to a full-scale, long-term program of many breeders now. Whether the prototype breeder now under construction is the appropriate one, or whether after its many delays it should be modernized or replaced, is a question which needs early decision. Our breeder program is essential but I can't see that even with the many past delays and our lag compared to other nations that our prototype construction should be a crash program. We should remember that while the breeder was an important part of our first U.S. reactor program (two of the four reactors were breeders), subsequent events and especially $2 a barrel oil kept the program at a very low level for many years.

As to the longer range programs of fusion and solar electric generation, we know that the latter is possible and the former looks hopeful. Whether either is economically feasible will not be determined soon. It is important, however, that both of these methods be worked on now. It may not be possible for a decade or more to tell whether one or the other will really be able to furnish our long-range energy needs. It is possible that unforeseen limitations of one method or the other may make it desirable to use both of these methods, both of which have essentially limitless fuel available.

Probably most important of all is that we develop a variety of energy sources, especially those on which we must depend for the mid- and long-term future. Presently unforeseen difficulties could make a program, now attractive, be non-viable in the future. Energy is too essential for us to take that risk. So far our government has failed to adopt any long-range energy plan, and there does not seem to be much chance of such a plan in the near future. That may not be catastrophic if we realize that any plan must change as new developments occur and that no single solution is possible. We must keep flexible and explore new possibilities and ideas on their merit. I am glad to see that ERDA has made flexibility the key to its research and development program. □

Robert F. Bacher was a member of the Los Alamos Laboratory during World War II, first as head of the experimental physics division and later as head of the bomb physics division. He served as a scientific advisor to Bernard Baruch during the U.N. Atomic Energy Commission negotiations in 1946, and was a member of the first U.S. Atomic Energy Commission from 1946-49. He served two terms as a member of the President's Science Advisory Committee and on various committees and panels of the Department of State, the Department of Defense and the Atomic Energy Commission. He has been at the California Institute of Technology since 1949, first as chairman of the division of physics, mathematics and astronomy, then as provost and now as professor emeritus.